Stable droplet generator for brightness LPP EUV source

Mikhail Krivokorytov*[1], Alexander Vinokhodov[1], Yuri Sidelnikov[1,2], Konstantin Koshelev[1,2], Vladimir Krivtsun[1,2], Viacheslav Medvedev[1,2], Denis Glushkov[3], Samir Ellwi[3]

1 – RnD-ISAN/EUV Labs, Troitsk, 142190 Russia; 2 – Institute for Spectroscopy RAS, Troitsk, 142090 Russia; 3 – ISTEQ, 5656 AG Eindhoven

* – mikhail.k@phystech.edu

Motivation

It' s well known that actinic inspection could be a possible solution for metrology applications in EUV lithography. EUV source challenges for actinic inspection are: Brightness, **EUV pulse-to-pulse stability**, life time.

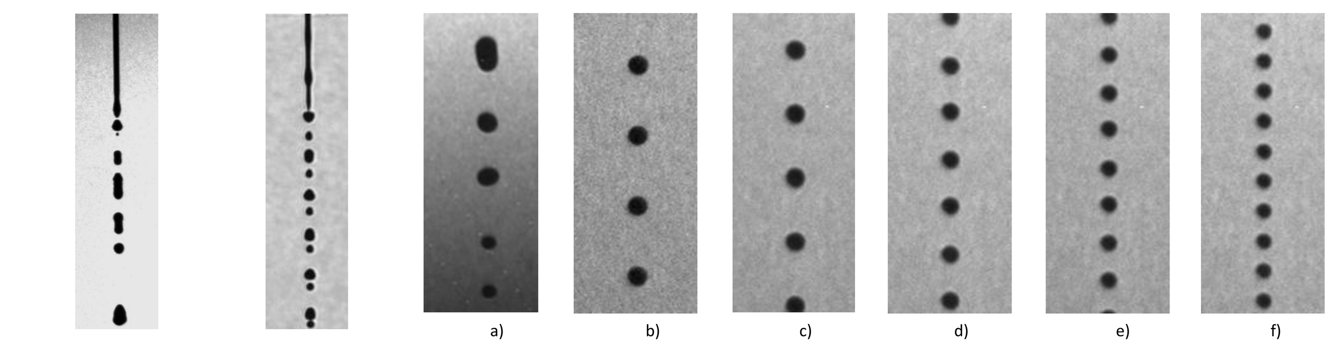
In case of LPP source based on tin droplets EUV stability is determined by laser stability (pulse energy and spatial & temporal distribution) and also **target stability.** The main requirements on target stability are:

Mass uniformity, position stability

This work presents an demonstration of droplet generator (DG) based on induced Rayleigh jet breakup operation. Data on its operation in terms of mass uniformity and position stability and also EUV pulse-to-pulse stability.

Main idea & physical phenomena

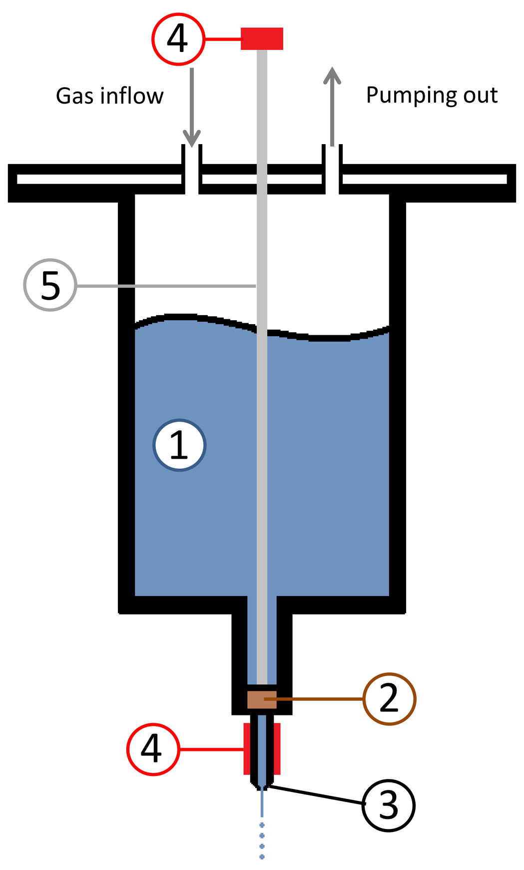
The **Plateau–Rayleigh instability**, often just called the **Rayleigh instability**, explains why and how a falling stream of fluid breaks up into smaller packets with the same volume but less surface area. It is related to the **Rayleigh–Taylor instability** and is part of a greater branch of fluid dynamics concerned with fluid thread breakup. This fluid instability is exploited in the design of a particular type of ink jet technology whereby **a jet of liquid is perturbed into a steady stream of droplets.**
The driving force of the Plateau–Rayleigh instability is that liquids, by virtue of their surface tensions, tend to minimize their surface area. A considerable amount of work has been done recently on the final pinching profile by attacking it with self similar solutions.



Instant shadow photographs (660 x 2670 um) of free jet breakup (left) and induced jet breakup (right)

Instant shadow photographs (280 x 700 um) of droplet train at distance ~ 20 mm from nozzle. Different excitation frequencies: a) no excitation; b) 40 kHz; c) 60 kHz; d) 80 kHz; e) 100 kHz; f) 125 kHz.

Basic design



The main parts of droplet generator are tank (Mo) with liquid metal (1) and nozzle (3). Tank connected to pump and gas (Ar) supply. With feeding the pressure in the tank the jet can be formed. Nozzle orifice diameter is tens of microns, to avoid a clogging of the nozzle the filter element (2) is used. Filter element is the tablet of sintered powder metal (stainless steal or Zr).

To modulate the jet breakup the piezo actuators (4) are used. Piezo element can be placed directly at the nozzle (hot zone), but majority of piezo ceramics begin to break down at temperatures above 250 °C, which puts restrictions on the operation of the droplet generator. Another way is to place the piezoelectric element (4) in a low (room) temperature and use the waveguide (5) to transmit of an external excitation to a tank with liquid metal.

Sn-In eutectic alloy (melting temperature 119 ˚C) are used as fuel in all presented experimental result.

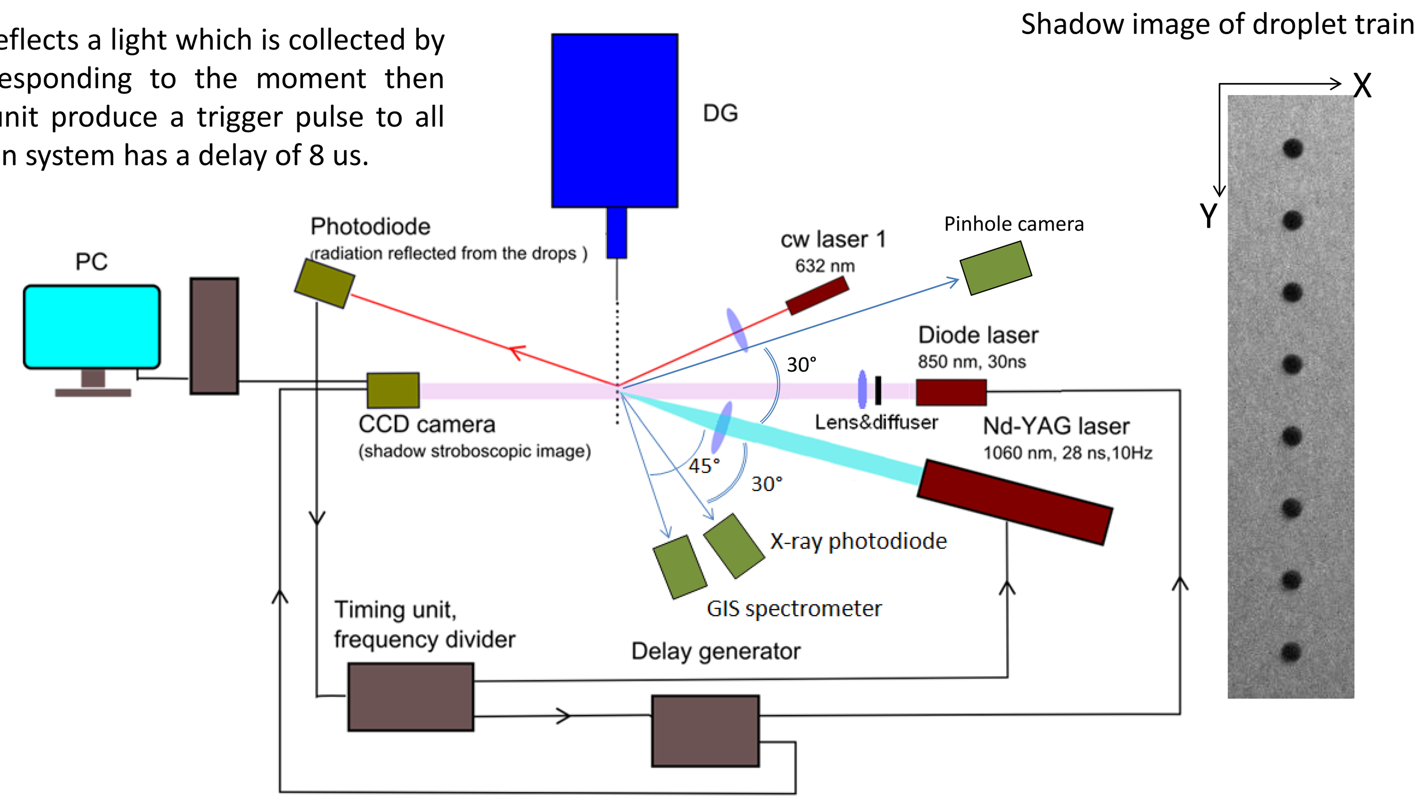
Experimental diagnostics & synchronization

The trigger from droplet system
The CW laser is focused on the droplet train, each droplet reflects a light which is collected by photodiode. Maximums of the photodiode's signal corresponding to the moment then droplets cross the center of CW laser focal spot. Timing unit produce a trigger pulse to all devices including Nd:YaG laser and CCD. Maximum detection system has a delay of 8 us.

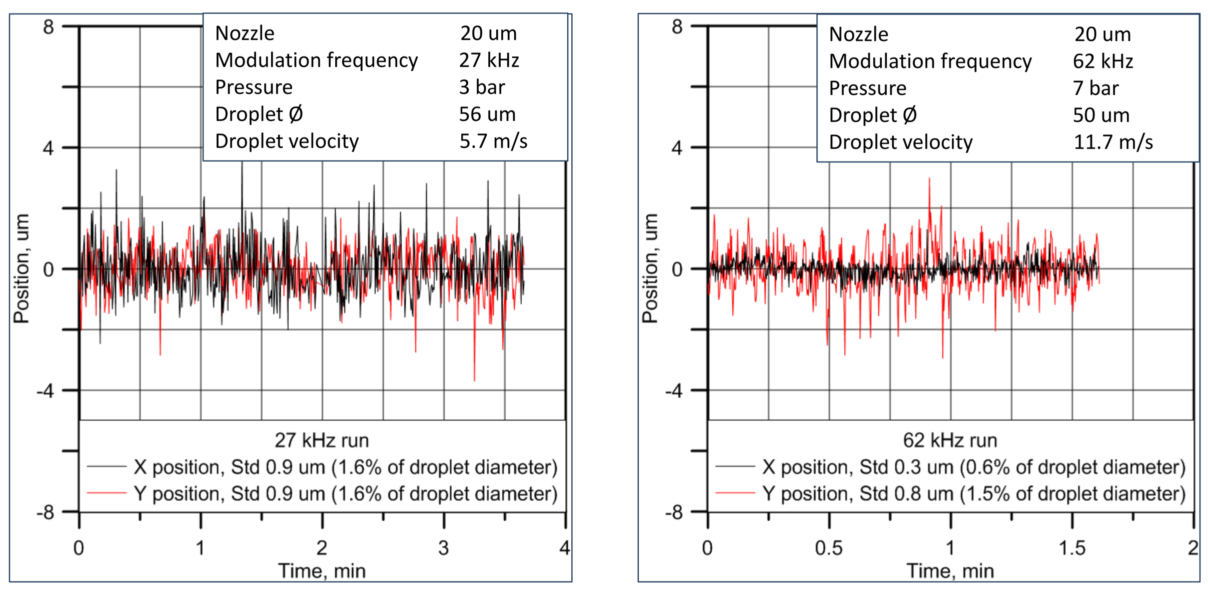
Image acquisition system
Shadow photograph in the divergent light beam
- Camera: Manta MG-145B
- Long-Distance microscope Model K2 DistaMax
- Laser: pulsed diode pumped IL30C
- Square Engineered Diffuser: ED1-S20-MD

Observed area 2.9 mm x 2.2 mm
Spatial resolution 2.3 um
Distance from nozzle ~ 40 mm
Sensitivity ~ 0.3 um

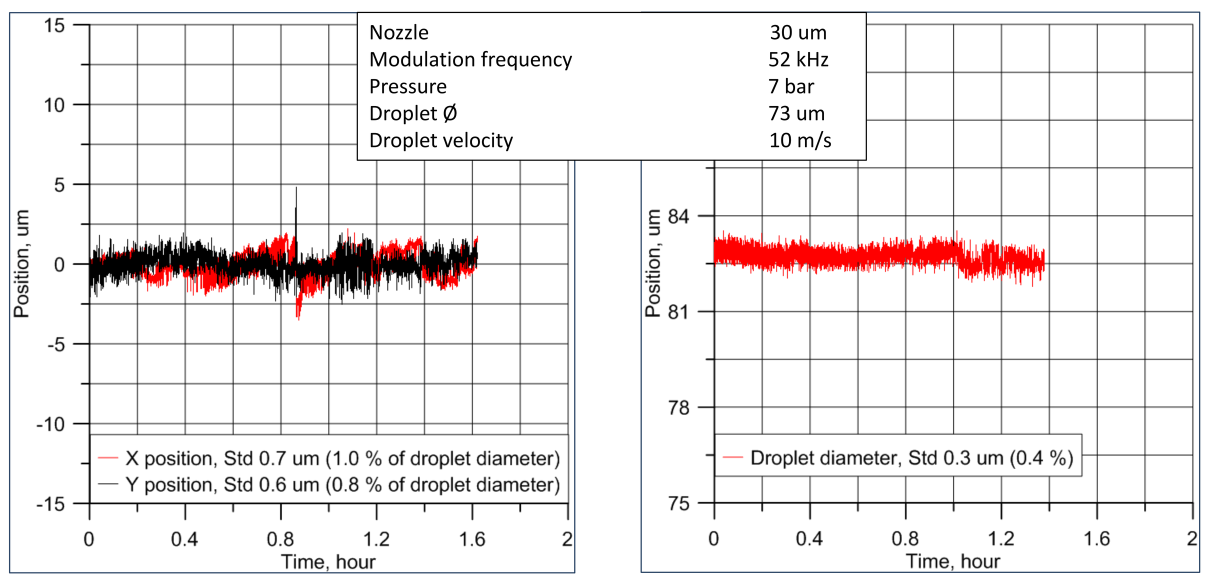
Plasma diagnostic
- pin hole camera: Zr filter, a pin hole, phosphor screen with a CCD camera
- X-ray photodiode with Mo/Si filter, 45˚ Mo/Si mirror
- GIS spectrometer



Examples of short & long DG operation



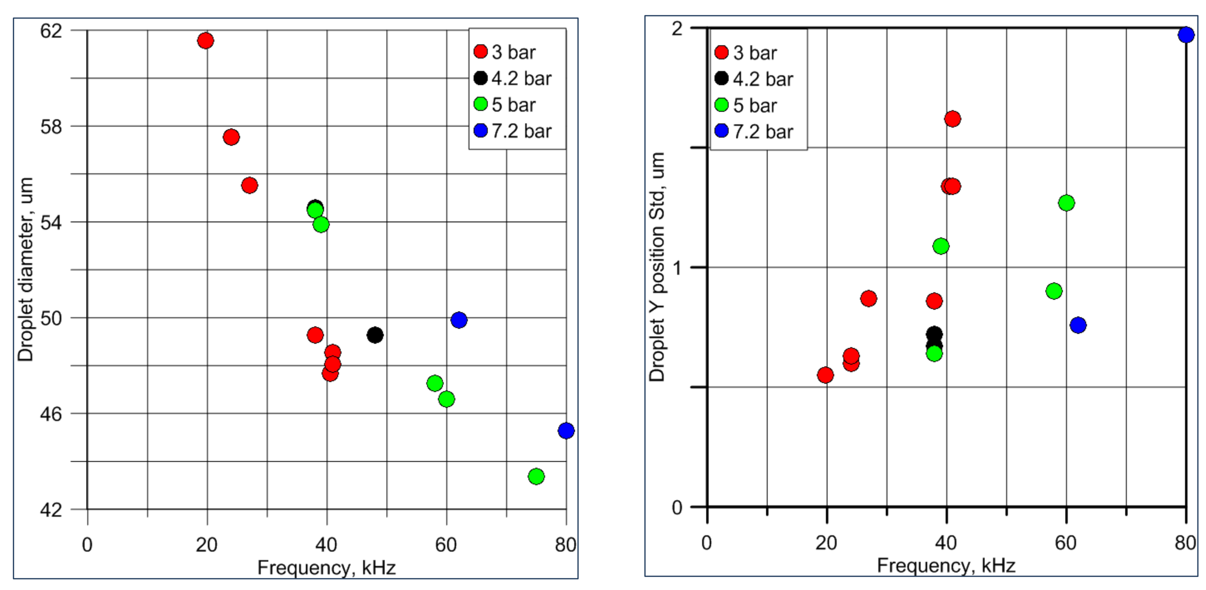
Short term: position stability. The same number (600) of droplets were recorded and processed



Long term: position stability & mass uniformity. One drop per second was recorded and processed

Examined conditions of DG operation

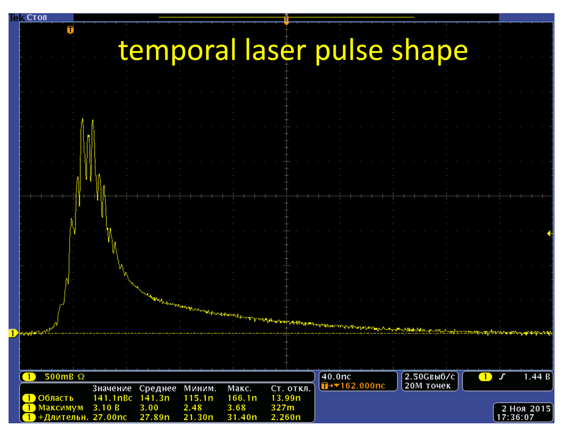
Data coupled during short term operation

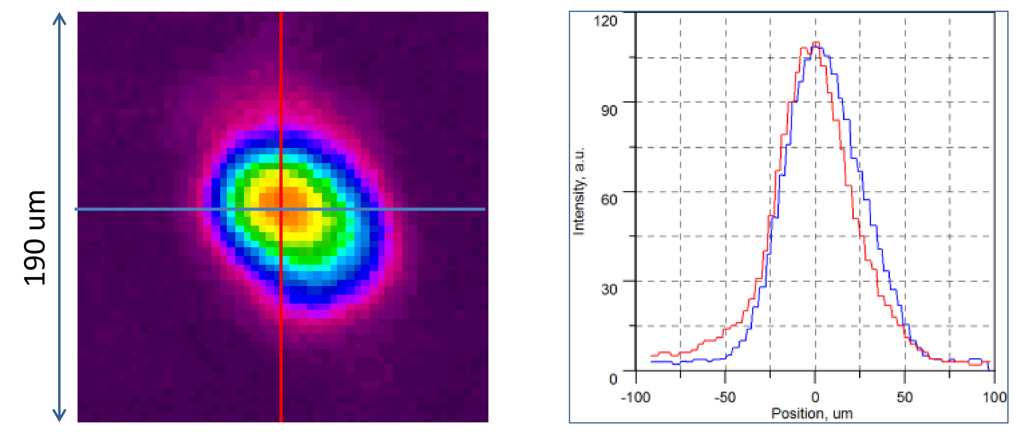


Proof of concept with 10 Hz Nd:YaG laser

Laser parameters

Parameter	Value (Std %)
Pulse energy, mJ	100 (9.9 %)
Peak intensity, MW	2 (10.9 %)
Pulse width, ns	28 (8.1 %)
Average power density at focal spot, W/cm²	$1.8 \cdot 10^{11}$ (13 %)

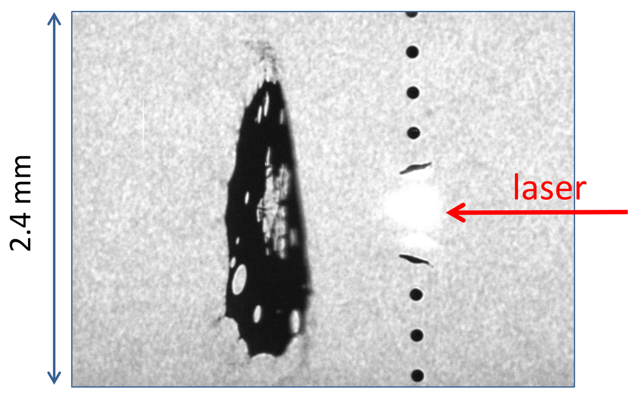




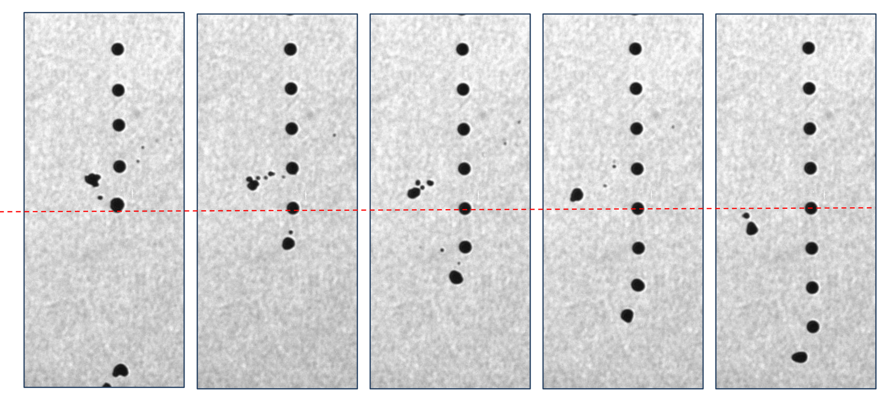
Intensity profile. Laser focal spot size ~ 50 um (FWHM)

Droplet parameters

Parameter	Value
Diameter, um	70
Velocity, m/s	9.6
Frequency, kHz	40
Period, um	240
Temperature, K	413
Material	Sn/In
X-Y position Std, um	$\sigma_x \approx \sigma_y \approx 0.5$ um



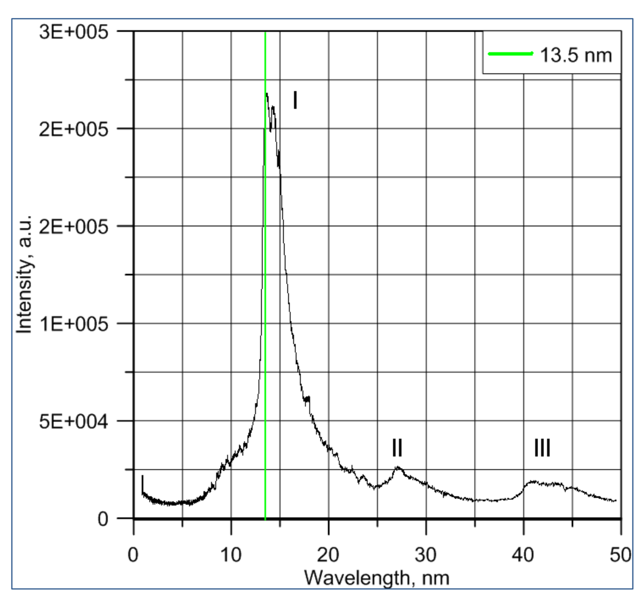
5 us after laser pulse



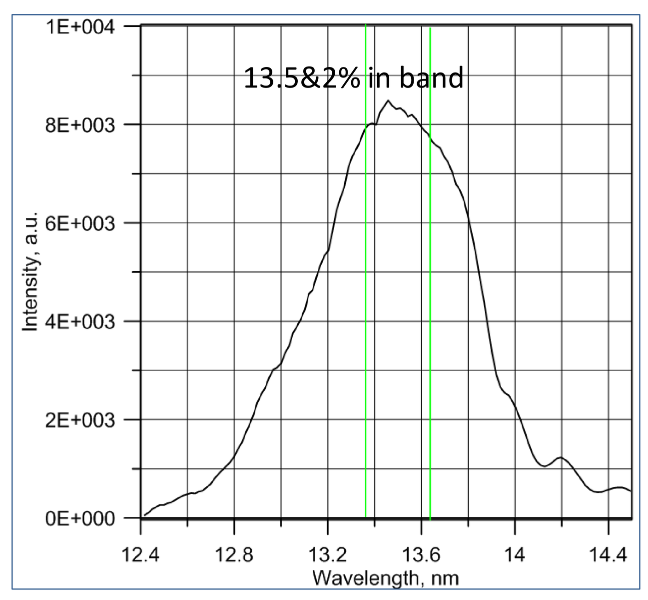
50 us 75 us 100 us 125 us 150 us

Laser frequency should be <13.3 kHz

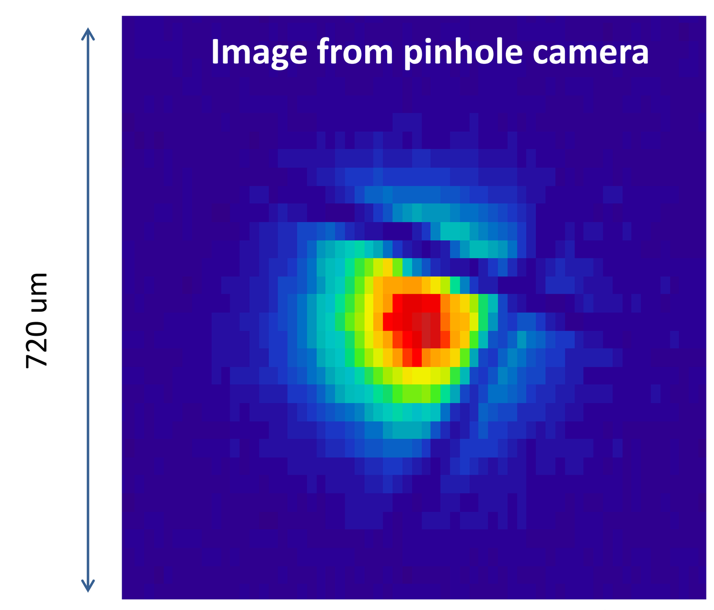
Emission spectrum, plasma size and brightness



4˚ GIS spectrometer; I, II, III – diffraction orders



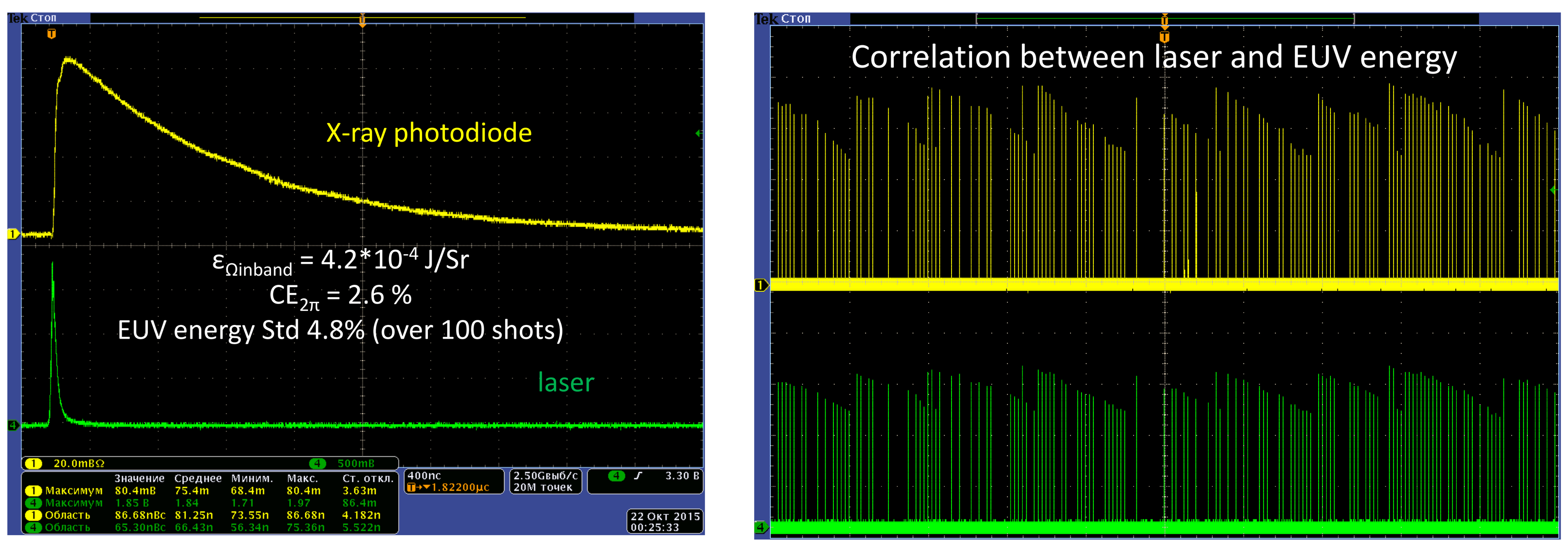
Emission spectrum at photodiode



Source size ~ 100 um (FWHM)

Scaling law for brightness

$B_{13.5} \approx 0.5$ W/mm²Sr (10 Hz)
$B_{13.5} \approx 50$ W/mm²Sr (1 kHz)
$B_{13.5} \approx 400$ W/mm²Sr (8 kHz)



EUV pulse-to-pulse stability can be improved via improving laser energy stability

CONCLUSION

1. The droplet generator based on induced Rayleigh jet breakup was developed.
2. The high droplet position stability and mass uniformity was demonstrated both in short & long terms of operation.
3. The flexibility of operation regimes (droplet diameter, velocity and frequency) was demonstrated.
4. Two types of jet modulation was developed: piezo in hot zone, which limits an operation temperature (250˚C), and waveguide with piezo at room temperature, which allows to operates with higher temperatures.
5. It was shown that such droplet generator can be used for high brightness and high stability LPP EUV source.

The work was supported by the Ministry of Education and Science of the Russian Federation under the Agreement № 14.579.21.0004 (a unique identifier for Applied Scientific Research (project) RFMEFI57914X0004).